Challenges and Recent Developments in Flood Forecasting in India

Sanjay Kumar*[1], Sharad Kumar Jain[1], Sunil Gurrapu[1]
[1] *National Institute of Hydrology, Roorkee*

Abstract: Floods are ranked among the largest and costliest natural disasters globally having major impact on various economic sectors. In India, flooding is one of the three prominent climate extremes, other two being droughts and cyclones. Flood forecasting and warning system is an important tool for effective management of water resources and for emergency response services. Across the globe, several flood forecasting tools have been developed to address specific or local challenges, but no single tool provides a complete operational solution that is applicable universally. In India, flood forecasts for major interstate rivers and projects are currently prepared and disseminated by Central Water Commission (CWC). However, the desirable lead-time and reliability for flood forecasting requires considerable improvements. The recent research and developments in flood forecasting attempt to consider rainfall forecasts, to significantly improve upon the lead-time to forecast flood. At present, India Meteorological Department (IMD) generates precipitation forecasts for short-range (up to 72 hours), medium range (4 to 10 days) and long range (30 days and up to one season), which may be used to generate short-range and medium range streamflow forecasts in a basin. The reliability of the streamflow forecast is based on the accuracy of the rainfall forecast, hydrological model and its parameters, and initial conditions. This paper has reviewed the ensemble framework adopted in streamflow forecasting across the globe and their applicability in Indian context with a focus to address the present gaps and challenges in flood forecasting. The review will provide an overview of this methodology and its relevance in operational flood forecasting. The paper also briefly describes the recent initiatives in India in this field.

Keywords: Flood Forecasting, Precipitation Forecast, Numerical Weather Prediction, Ensemble, Hydrological Models, Uncertainty.

1.0. Introduction

Floods are among the most frequent and devastating climate related disasters (ICHARM, 2009; UNISDR, 2012). Each year floods strike many regions in the world and result in huge loss of life and property. The trends in flood damages have been increasing exponentially primarily due to growing population, investments in flood affected areas and changes in land-use patterns in upstream regions. It is also likely that flooding would be more frequent and widespread in future due to extreme weather events perceived to be induced by changing climate (ICHARM, 2009; Vogel et al., 2011; Roxy et al., 2017). In addition, the social and environmental changes are further expected to increase the risk and cost of these natural disasters. This initiated the widespread debate among stakeholders to adopt appropriate counter measures to alleviate the persistent threats of flood disasters (Linnerooth-Bayer and Amendola, 2003; Arduino et al., 2005).

Past experiences indicate that the floods and their impacts can be mitigated but cannot be eliminated completely (Moore et al., 2006). Despite this, the measures of flood risk mitigation can be categorized into three major categories, i.e. structural, non-structural and a combination of the two (G. Rossi et al., 1994; Jain et al., 2018). The structural measures include

* corresponding author, skumar.nih@gmail.com, +91 94121 58646

construction of reservoirs, embankments, levees, dikes, diversion channels, etc. and these measures can influence or change the flood characteristics. The non-structural measures includes early flood warning, flood plain zoning, flood proofing and flood insurance programs. These measures are intended to change the flood impacts and their consequences without changing their characteristics. In spite of historical benefits of structural flood control measures, the current emphasis is majorly on the non-structural measures. The major advantage of non-structural solutions of flood mitigation is that the adverse ecological and environmental impacts of the structural measures can be avoided. The other measure of flood risk mitigation is the judicious combination of structural and non-structural flood mitigation measures. The natural way or the fourth measure of flood risk mitigation is by adapting to the floods and learn how to live with floods wisely, i.e. getting adjusted to the floods by minimizing the negative and maximizing the positive aspects (Arlikatti et al., 2017). Overall, disasters from severe floods can be prevented by an effective early warning and forecasting system (National Weather Service, 2010).

A flood warning and a forecasting system is a valuable tool in reducing the vulnerabilities and flood risk. Significant technological advances have helped the betterment of real-time flood forecasting and warning systems (WMO, 2011; Roy et al., 2012; Barbetta et al., 2016). The application of satellite and weather radars for rainfall monitoring significantly improved the capability of these systems in detecting potential rainfall events that may cause flooding and the warnings are issued several days ahead when compared to the flood forecasting systems based on the observed rainfall and streamflow. In this context, this paper reviewed several existing flood warning systems and their integration with numerical weather prediction models in an ensemble framework across the globe. One of the major objectives of this study is to review the applicability of these systems to the watersheds of India with a focus to address the present gaps and challenges in flood forecasting and warning. The review will provide an overview of the methodology, its relevance in operational flood forecasting and briefly describes the recent initiatives in India in this field. This paper discusses the use of various rainfall prediction products generated by the India Meteorological Department (IMD) to issue short-range (up to 72 hours), medium-range (4 to 10 days) and long-range (30 days and up to one season) flood warnings.

2.0. Flood Warning and Forecasting Systems

A typical flood warning system (FWS) consists of three major components including (a) flood detection, (b) flood forecasting & warning and (c) flood response, Figure 1 (Vogelbacher, 2013). Flood detection phase involves continuous monitoring of hydrological and meteorological data from the catchment of interest. Flood forecasting involves the use of hydrologic and hydraulic models to generate possible extent of flooding using the real-time hydrometric data and the precipitation forecasts. Flood warnings are issued in this stage based on the flood forecasts made. Efficient meteorological forecast systems help in increasing the lead-time of the flood warnings. Following these warnings, the authorities/communities take appropriate measures in response to the forecasted flood to reduce the damage through flood preparedness. Several studies from the recent past highlight the advances in flood forecasting and warning systems (e.g. Moore et al., 2006, Sene, 2008, Hapuarachchi et al., 2011, Nester et al., 2012, Jain et al., 2018). These systems operate at varying spatial scales including local, basin-wide, regional, national, global and continental (e.g. Hopson and Webster, 2010; Alfieri et al., 2013; Thiemig et al., 2015). These systems are generally tailor-made to suit the specific operational requirements depending on the type of flood and its scale. For example, flash flood may provide very little time for response and therefore requires very accurate forecasts of real-time precipitation. Similarly storm surge flooding (resulting from a cyclone or hurricane) requires unique characteristics for storm tracking (Madsen and Jakobsen, 2004; Jain et al., 2018).

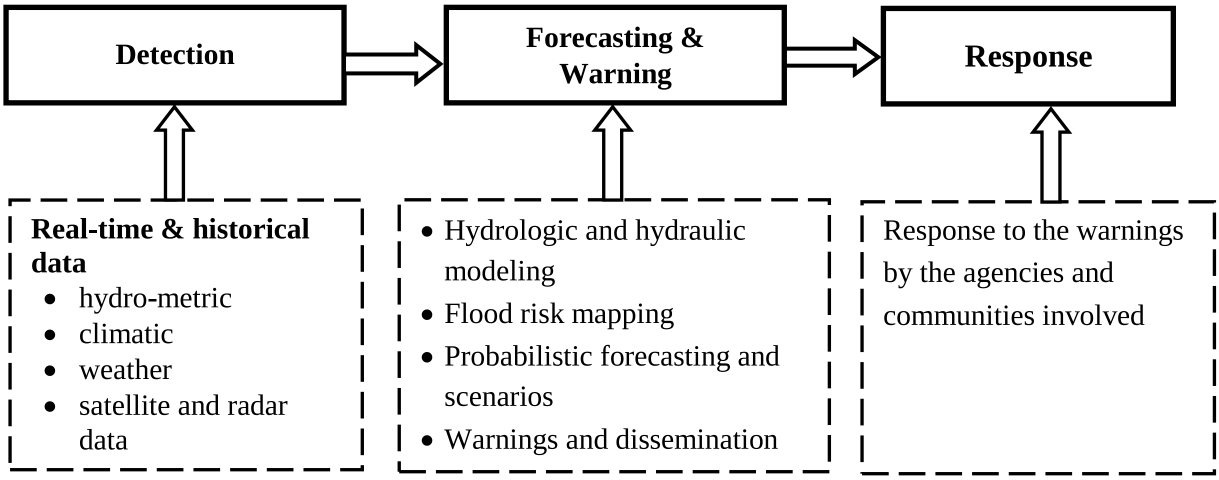

Figure 1: A schematic diagram of flood warning and response system

2.1. Flood Forecasting Models

Hydrological models are capable of simulating future estimates of a selected hydrological variable, water level, streamflow, etc. at a particular location. They are typically based on the method of applied system analysis, Figure 2 shows a typical system of a hydrological model having precipitation $P\ (t)$ as a primary input which is transformed to discharge $Q\ (t)$ as an output by a transfer function $F\ \{P\ (t)\}$ (Vogelbacher, 2013). Hydrological models have evolved over time with the recognition of flood warning as an important measure for flood management and constitute the heart of any flow forecasting system (Serban and Askew, 1991; Rossi et al., 1994). For example, a simple extrapolation technique, which was popular earlier is no longer sufficient as the flood characteristics, i.e. magnitude and frequency, have changed significantly (Moore et al., 2006). In addition, the lead-time of a forecast, i.e. the period between the time of issuing the forecasts and the time of actual occurrence, varies significantly with the basin characteristics in addition to the precipitation characteristics (WMO, 2011).

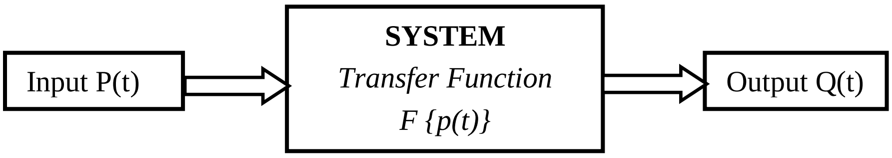

Figure 2: System components of a typical hydrological model

Experiences show that each hydrological model is unique and every model has its own merits and demerits. Jain et al. (2018) described the merits and demerits of several hydrological models for flood forecasting based on several criteria. In addition, several other studies from the past discussed the advantages and disadvantages of hydrological models based on their use, either for flood forecasting or flood planning (e.g. Plate, 2009; Kauffeldt et al., 2015). The major difference between the forecasting and planning models is the required accuracy, forecasting models require higher accuracy than the planning models. Forecast models are expected to produce an exact or near-exact magnitude of peak flood, in contrast to that expected from a planning model. As a general rule a model should have low forecasting uncertainty (WMO, 2011). Updating techniques (or data assimilation) are used to reduce the uncertainty in model outputs. This feedback mechanism which combines the model output and the observations is an essential component of a flood warning system. The model forecast is primarily a function of input variables, state variables, model parameters and model structure. Refsgaard (1997) described four approaches for updating the flood forecasts, viz. updating input variables, state variables, model parameters and updating with error prediction, Figure 3. The first approach is associated with the updating of input variables, which necessarily pertains to the correction of precipitation data provided as an input to the model. In the second approach, the state variables are varied within their threshold levels and Kalman filtering method is commonly adopted for updating the state variables. Model uncertainty can also be reduced by adjusting the model parameters as a function of output errors. In the fourth and last approach, the model error is forecasted and the model forecast is updated by adjusting the model error forecast based on its statistical properties.

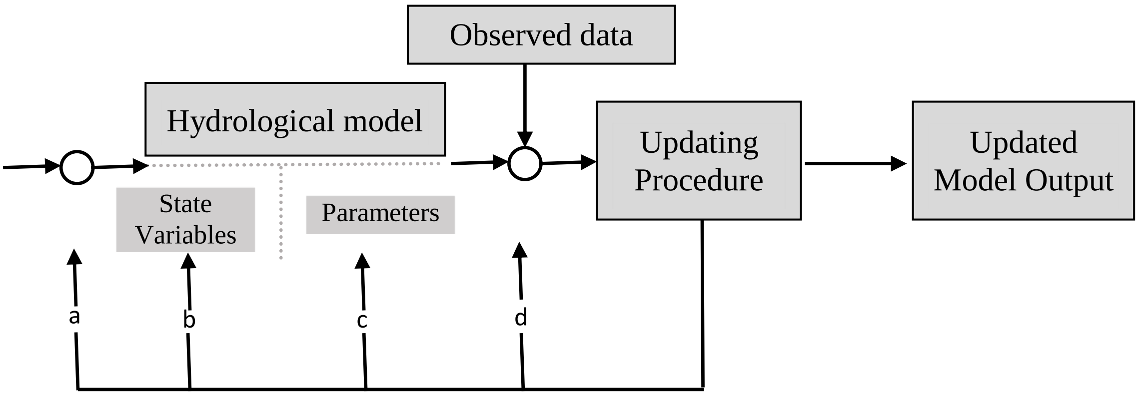

Figure 3: Model updating approaches (Refsgaard, 1997)

The catchment characteristics such as the drainage behavior at a forecasting site is an important information required in deciding the forecast model and the required input dataset in order to produce a reliable forecast. Table 1 lists out different types of landscapes and flood type associated with each of them. The achievable lead-time of the forecast at a forecasting site is primarily dependent on (a) the time of travel to the highest flow, (b) the time to peak and (c) time of concentration of the catchment (Werner et al., 2006). When the channel flow time is greater than the time of overland runoff, forecast can be made using channel flood routing based on the upstream gauge measurement. In contrast, if the channel flow time is less than the time of overland flow, concentration of runoff dominates and so the lead-time is based on the time to peak. In such situations, the forecast is dependent on real-time precipitation measurements. However, many-a-times the desirable lead-time to forecast is greater than the time required for channel flow and the overland flow. In such situations, precipitation forecasts are needed and so the hydrological models are integrated with the meteorological models to get sufficient lead-time. These situations are mostly common in small catchments affected by flash floods.

Table 1: Different type landscape and their flooding behavior (Plate, 2009)

#	**Type of Landscape**	**Type of Flood**
1	High mountain ranges	Flash floods and geophysical flows.
2	Foot hill regions	Floods are caused by intense rainfall (or snowmelt).

3	Plain regions	The flow velocities are very low and the landscape do not have sufficient flow capacities to pass high incoming flows, resulting in flood situations.
4	Urban areas	Flooding is primarily a result of inadequate drainage
5	Coastal areas	Floods result from cyclones and storm surges.

3.0. Meteorological Monitoring and Forecasts

The vital information required for an effective operational flood forecasting and warning systems is the real-time monitoring of the hydrological and meteorological data within the catchment. The real-time data is used not only for model updating but also to track the real situation through data assimilation (Warner et al., 2006). This data includes precipitation observations from several rain gauges and water levels (discharge) from river gauges. The catchment rainfall is usually estimated from the point rainfall measurements; however, the use of weather radars provides a better solution to capture the spatial variability of rainfall. Therefore, spatial coverage of the observed rainfall can be improved by integrating rain gauge data with radar rainfall estimates, which also helps in improving the reliability of the parameters of the distribution (Warner et al., 2006). In addition, satellite based rainfall estimates (finest resolution around 4 km^2) also efficiently capture the spatial variability in observed rainfall (e.g. Krakauer et al., 2013; Alazzy et al., 2017; Mishra and Rafiq, 2019). Satellite precipitation products are available from various institutes/organizations from across the globe. For a better temporal and spatial resolutions of precipitation data, different combinations of observed, radar and satellite datasets may be explored (e.g. Porcú et al., 1999; Dinku et al., 2014).

3.1. Numerical Weather Prediction (NWP)

Rainfall information constitutes an important input to flood warning and forecasting systems, which is obtained from rainfall gauges and radar data. For a longer lead-time (longer than the catchment concentration time), integration of numerical weather prediction (NWP) models with flood forecasting models is required. NWPs also add value to the prediction of floods with shorter lead-times (Cloke, 2009). NWPs are one among the many modern-day weather forecasting techniques developed through simplified systems of physical laws of the atmosphere (Wiston and Mphale, 2018). These models are available as both global and regional models. The regional models or limited-area models (LAMs) are defined for a particular section of the atmosphere. Most recent NWP models are able to provide 1–15-day quantitative precipitation forecasts, which can be coupled with a hydrological model to produce flood forecasts with longer lead-times. Several flood warning systems have been developed and implemented across the globe (e.g. Pappenberger et al., 2005; Thielen et al., 2009; López-Trujillo, 2010; De Kleermaeker et al., 2012; Doong et al., 2012). Table 2 provides a list of operational (and pre-operational) flood forecasting systems using ensemble weather prediction as inputs for flood warning and forecasting. In India, LAMs are developed and operated by IMD and National Centre for Medium Range Weather Forecasting (NCMRWF) (Rathore et al., 2017; Rao et al., 2006). For example, Goswami et al., 2018 used the meteorological output from NCMRWF Unified Model (NCUM) to evaluation the SWAT model in simulating surface runoff in Narmada River basin during monsoon season. Establishing an early flood warning system to reduce disaster losses is the most cost-effective solution of all of the structural and non-structural measures studied (Alfieri et al., 2012; Hallegatte, 2012).

Table 2 List of flood forecasting systems using ensemble weather predictions as inputs

#	Ensemble NWP input	Forecast System / Centre
1	European Centre for Medium Range Weather Forecasts (ECMWF)	1. European Flood Alert System, EFAS (Thielen et al., 2009; Smith et al., 2016) 2. Climate Forecast Applications in Bangladesh, CFAB (Hopson and Webster, 2008) 3. Finnish Watershed Simulation and Forecasting System, WSFS (Vehviläinen and Huttunen, 2002) 4. Swedish Meteorological and Hydrological Institute, SMHI (Olsson and Lindström, 2008) 5. Royal Meteorological Institute (RMI), Belgium (Roulin, 2007) 6. Ensemble Streamflow Prediction System, Meteo France (Rousset-Regimbeau et al., 2008) 7. Hungarian National Hydrological Forecasting Service, NHFS (Bálint et al., 2006)
2	Consortium for small-scale Modelling limited-area ensemble prediction system (COSMO-LEPS)	1. European Flood Alert System, EFAS (Roo et al., 2011; Smith et al., 2016) 2. Forecast demonstration project, Mesoscale Alpine Program, MAP (Rotach et al., 2009) 3. Bavarian Flood Forecasting Centre (Hangen-Brodersen et al., 2008)
3	US National Oceanic and Atmospheric Administration (NOAA)	Advanced Hydrologic Prediction Service, AHPS (McEnery et al., 2005)
4	NCMRWF Unified Model (NCUM)	NCMRWF (Goswami et al., 2018)

3.2. Weather Observations and Forecasts

The IMD prepares rainfall distribution summaries at different temporal (daily, weekly, monthly etc.) and administrative scale (district, sub-division, state, etc.) using real-time precipitation data. At regular intervals, IMD prepares rainfall maps for at least 36 meteorological sub-divisions of the country, which shows weekly and cumulative rainfall. In addition, IMD (http://www.imd.gov.in/section/hydro/QPF/WRF/) provides real-time precipitation data at an hourly timescale for several meteorological stations. IMD has set up nearly 10 Flood Meteorological Offices (FMOs) across the country viz., Agra, Ahmedabad, Asansol, Bhubaneshwar, Guwahati, Hyderabad, Jalpaiguri, Lucknow, New Delhi, and Patna. These FMOs provide details to the Central Water Commission (CWC) for issuing flood warnings in the watersheds associated with each FMO. In addition, National Centre for Medium Range Weather Forecast (NCMRWF) publishes several weather forecast products based on several outputs from numerical models.

A 3-day forecast or rainfall and wind over Indian subcontinent is published daily on the website of NCMRWF, and these are generated using a regional unified model (UM-REG) with spatial resolution of 4 km. These forecasts also provide warnings of severe weather with a lead-time of 3-days (https://www.ncmrwf.gov.in/product_grid_ind_mihir.php). NCMRWF also publishes a 10-day forecasts of precipitation and wind, which are generated from a global unified model, or NCMRWF unified model (NCUM) (George et al., 2016). NCUM is based on the Unified Model (UM) developed under the partnership by Meteorological departments of several countries including UK, Australia, South Korea, New Zealand and India. Recently, the horizontal resolution of these models (NCUM) is increased from ~17 km to ~12 km (Kumar et al., 2018). NCMRWF also uses a global ensemble prediction system (NEPS) to generate a 10-day forecast, from an ensemble of 22 members (Chakraborty et al., 2019). These forecasts are issued four times a day, viz. 00:00, 06:00, 12:00, and 18:00 hrs. In addition to the weather forecasts over Indian subcontinent, NCMRWF also publishes weather forecasts for the neighbouring monsoon region. IMD also publishes quantitative forecasts of precipitation based on the WRF model with a grid length of 9 km and a lead-time of 3 days.

4.0. Early Flood Warning System

The global survey of early warning systems by United Nations (UN) in 2006 identified four major elements required to develop a natural hazard early warning system viz., (a) Risk knowledge, (b) Monitoring and warning services, (c) Dissemination and communication, and (d) Response capability (UN, 2006). Risk knowledge is associated with the systematic assessment of a natural hazard and its vulnerabilities, which includes mapping of their patterns and trends. Accurate forecasting of a hazard with adequate lead-time is of utmost importance, which can be done using a reliable, scientific methods and technologies. Such information should be clear and an appropriate warning should be communicated to all the communities at risk. Finally, these communities should be given appropriate training on how to respond when such warnings are communicated. In a similar pattern, the basic structure of an early flood warning system (EFWS) requires (a) numerical weather-prediction models to provide specific rainfall forecasts (both quantity and timing) (b) Network of hydrometric stations (automated/manual) linked to a central control body by telemetry and (c) a flood forecasting model using the above information in real-time to provide appropriate forecasts and warnings. The layout of a typical early flood warning system is shown in Figure 4. The components enclosed in a dashed box in this figure needs to considerable improvements at institutional level for this system to be implemented in India. It is important to note that the flood warnings are distinct from forecasts since they are issued when an event is about to happen or already occurring. The flood warnings can be used for various purposes such as giving individuals and organizations time to prepare and in extreme cases, undertaking evacuation and emergency procedures.

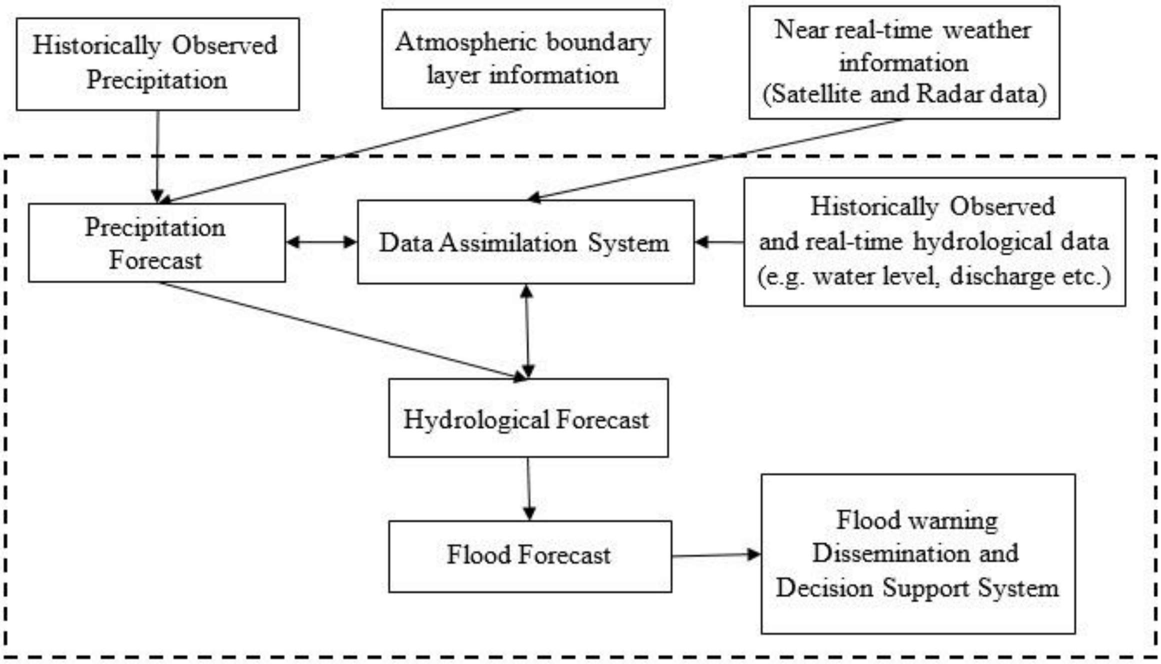

Figure 4 Layout of a typical early flood warning system

4.1. Flood Warning Dissemination

The flood warning and dissemination process is a complex and critical component of a flood warning system, which primarily includes (a) generation of flood forecasts, (b) issuing flood warnings to the end users, and (c) flood response. The success of an EFWS depends on the accurate forecast, adequate planning and promptness in communicating the flood warnings with sufficient lead-time. The communities exposed to the flood hazards will be benefitted by an accurate flood forecast with adequate lead-time will benefit the communities directly exposed to the flood hazards. This provides them with enough time to evacuate the vulnerable group of people who may not be able to respond quickly to the warnings (i.e. very young, old and mobility-limited persons), move their assets to a safer location (i.e. livestock, food, moveable goods etc.), efficient and timely operation of flood regulation infrastructure and initiation of flood response measures (Wood et al., 2015; Cova et al., 2017). It is important to note that a flood can be predicted with higher accuracy only during the later stages of its development when near real-time information on precipitation and streamflow upstream become available. Therefore, for a longer lead-time it is necessary to accept prediction, although less accurate. Figure 6 shows a trade-off between the warning accuracy and lead-time (warning time) available. It shows that the flood forecasts & warnings are less accurate based on meteorological outlooks, whereas these warnings are more accurate after the onset of a storm.

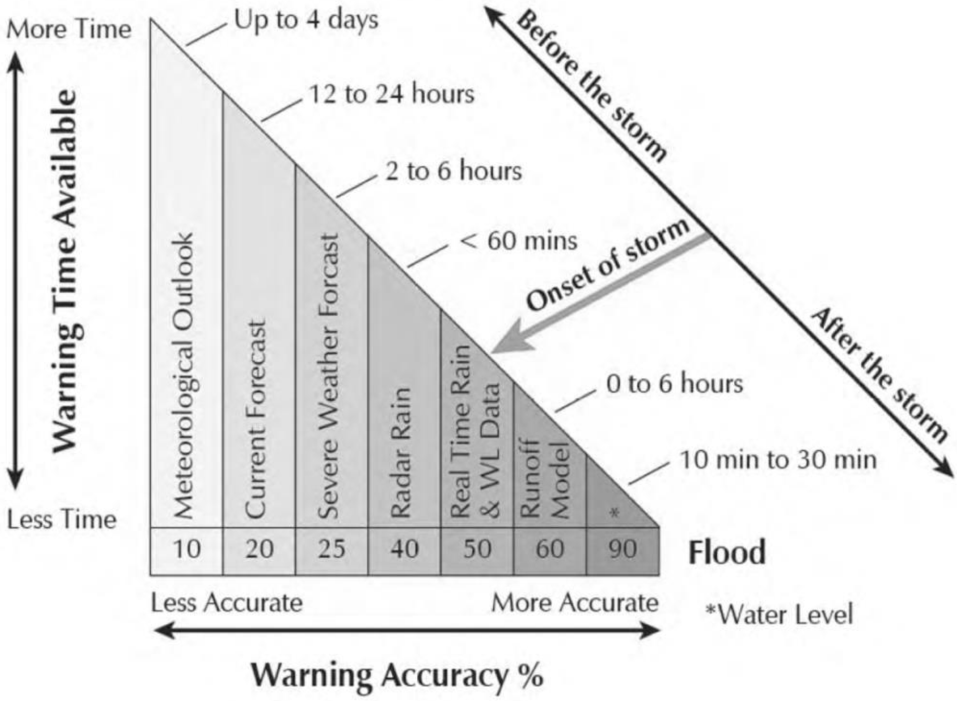

Figure 6 The trade-off between warning time and flood forecast accuracy (WMO, 2011)

5.0. Uncertainty in Early Flood Warning Systems

There are basically four sources of uncertainty in the flood forecast. These are (a) input data uncertainties, (b) uncertainty in model specification, (c) uncertainty in model parameter estimation and (d) operational practice of forecast generation. All these sources of uncertainty affect the reliability of the simulated output. The uncertainly in the flood forecasts is known to increase the lead-time (Laurent et al. 2010). In many cases, precipitation forecasts are the most dominating source of uncertainly in flood forecasting with a lead-time beyond 2-3 days. Relative importance of these sources of uncertainty varies with lead-time, magnitude of the event and catchment characteristics. Cloke et al. (2009) mentioned that input uncertainties propagating the forecast system can be increased or decreased (or neither) according to complex interaction of the system components. These limits largely depend on the interaction between catchment response time, catchment characteristics and resolution of the input data. For example, Thirel et al. (2008) show that an ensemble with larger resolution performs better for large catchments and low flows, whereas a high resolution ensemble is superior for small catchments with high flows. Precipitation forecast from each model differed significantly from the other (and also different runs from the same model). An appropriate method to quantify uncertainty from all the above mentioned sources would be to run the model several times by randomly varying the sources of uncertainty within its spectrum, e.g. Monte Carlo simulations. Overall, analysis and experience with the forecasts indicate that the accuracy can always be improved. However, the reduction of uncertainty in the data, the model and its operation should be the primary goal.

The major source of uncertainty in a weather forecast model is the error, however small, in the initial conditions of the forecast model (Lorenz, 1969). To address the concerns from such uncertainties, probabilistic weather forecasting (PWF) has now become a routine and its advantages are widely appreciated. PWF provides a range of plausible forecast solutions, which allows the forecaster to assess possible outcomes, estimate the risks and probabilities of those outcomes and to gauge the level of confidence in the final forecast. Earlier implementation of PWF was based on applying small, random perturbations to the initial conditions. However, the sources of uncertainty are not limited to the initial conditions and the uncertainty in model building plays a critical role (Slingo and Palmer, 2011). Uncertainty in NEPS forecasting model from NCMRWF is accounted for by making small perturbation in the initial conditions using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001) and by making small random variations to the model using stochastic kinetic energy backscatter scheme (Tennant et al., 2010). It is also important to distinguish between the model uncertainty that arises from imperfect knowledge of the real system, and uncertainty that comes from regional phenomena that are understood quite well, but are inadequately represented in the model. The effectiveness of probabilistic methods in weather forecasting depends on the reliability of the ensemble, where reliability in this context means that there is a proper representation of the forecast uncertainties. Nevertheless, no matter how much the models improve, there will always be an irreducible level of uncertainty because of the chaotic nature of the system (Slingo and Palmer, 2011).

6.0. Challenges and Prospects

The difficulties in estimating (and observing) rainfall continuously over space has constrained the advances in flood forecasting and warning. While weather radar in combination with rain gauge observations have offered the prospect of progress, there have been significant concerns to be overcome. To address some of these concerns, IMD has installed Weather Doppler Radars at several locations across the country and these helped in significantly improved the operational forecasting of thunderstorms (Roy et al., 2019). In addition, the advances in satellite remote-sensing and numerical weather prediction models will be a major help in addressing several challenges in flood forecasting. Flood forecasting and warning systems in integration with the rainfall monitoring and forecasting are currently adopted in many countries across the globe. In India, despite the substantial technical progress, several challenges from an operational point of view needs to be addressed for successful implementation of such a system. Challenges in particular include communicating risk information and early warnings to the responder agencies (disaster management agencies) and to the population at-risk (Cools et al., 2016). In addition, these agencies or the population at-risk should also be trained to respond to these warnings and trigger an appropriate response action.

These challenges can be categorized as technical, financial, institutional and social challenges (Perera et al., 2019). For example, integration between technical (risk knowledge, monitoring and forecasting components) and nontechnical (warning dissemination, communication and response capabilities) components of EFWS i.e., between institutions responsible for flood forecasting and those responsible for disseminating this information needs to be strengthened continuously. In addition, another major challenge arises from the uncertainties in the flood-forecasting techniques and subsequent decision making. Despite the challenges outlined above, institute/organizations designated with the responsibility of flood risk reduction should take advantage of the best available data products (real-time), tools with better computing techniques and resources, and new communication channels for better connection with the end users (Perera et al., 2019).

7.0. Discussion

India has highly diverse geography and climate and so are its flooding problems and their causes. In India, major concerns with respect to floods are inundation, drainage congestion due to urbanization and bank erosion. These concerns depend on the river system, topography of the region and flow phenomenon. Government of India has made huge investments in flood control sector since 1951 but the fears about flood severity and the agony brought out by them still persist and tends to increase with time in several places across the country. It is also expected that climate change and variability may increase the intensity and frequency of such flooding events in future (Singh, 2007; Planning Commission, 2011; Roxy et al., 2017).

Providing absolute protection to all flood prone areas against all magnitude of floods is neither practically possible nor economically viable. Hence a pragmatic approach in flood management is to provide a reasonable degree of protection (which is also economically viable) against flood damages through a combination of structural and non-structural measures. In addition, integrated flood management provides a paradigm shift from the traditional, fragmented and localized approach, and encourages the use of the resources of a river basin as a whole. Therefore, there is a need for an approach backed by the technological advances in hydro-meteorological monitoring, modelling, computing, and communication to provide timely and accurate warnings for disaster risk reduction. Forecasting and management of inland floods is more challenging than the coastal floods associated with the cyclonic storms. Although the processes leading to flooding from cyclonic storms is principally different from that of the processes causing inland flooding, it is worth learning from the successful execution of the cyclonic early warning systems. Cyclonic storms were forecasted by the cyclone warning division of IMD with better accuracy and the local authorities play a crucial role in disseminating this information and executing the appropriate response action. For instance, accurate forecasting of Phailin cyclone by the IMD in 2013, the timely warnings issued by the state Government of Odisha and the execution of appropriate response action by the district and other local authorities played a significant role in reducing the disastrous impacts of the cyclone Phailin (Kotal et al., 2013). Several advances were also made in inland flood forecasting, for example many pilot projects were taken up during the second phase of Hydrology Project (HP II) to demonstrate the technological advances in inland flood forecasting (MoWR, 2014). Few of these projects are currently operational, viz. Bhakra Beas Management Board (BBMB), and Water Resources Department, Government of Maharashtra. Early warning systems were also developed for several cities across India with the assistance from various international and national agencies (Karanth and Rajasekar, 2014). Modernization and evolution of better methodologies is a continuous process of any organization entrusted with the responsibilities of early warning and forecasting of severe flood events and these have been undertaken substantially by CWC and IMD. However, there is a need for capacity building and trained manpower keen to adopt technological advancements and implementation of such early flood warning systems.

This paper has reviewed early flood warning systems (EFWS), their components and their integration with the real-time meteorological forecasts from NCMRWF to generate flood forecasts with a lead-time greater than the catchment concentration time. The increasing deployment of EFWSs is majorly driven by two reasons, the first being the increasing technological advancements and the second being the international commitment made in the 2005 UN Hyogo Framework for Action, which was renewed in the 2015 Sendai Framework for Disaster Risk Reduction (UN, 2015). The technological advancements include (a) better forecasting techniques and (b) improved technology for better communication and information sharing (Webster, 2013; UNISDR, 2015). The availability of high resolution datasets such as radar nowcasting and ensemble weather forecasting, and increased computing capabilities have helped in increasing the accuracy of early flood warnings (Alfieri et al., 2012; UNEP, 2012; UNISDR, 2015). Several studies from the recent past illustrate the benefits of early warning systems (Roger and Tsirkunov, 2010; World Bank, 2011; Bouwer et al., 2014). These systems not only help in the disaster risk reduction, but also help in evaluating the adaptation to changing climate (Hallegatte et al., 2012; Zommers and Singh, 2014). Despite the technological advancement, implementation of these systems is yet a challenging task from the operational viewpoint, in particular, correctly communicating the risk information and warnings to the population at risk and triggering appropriate response actions. Several studies indicate that the potential benefits of EFWS cannot be materialised if the warnings are not understandable, useable or does not result in response action from communities (Hellmuth, 2007; Zommers and Singh, 2014; Baudoin et al., 2014; UNISDR, 2015). These studies have also cautioned about the variability, uncertainty and communication of ensemble information, suggested for a decision support system for an efficient response to the warning issued. In addition to the effective implementation of the early flood warning systems, understanding the uncertainty associated with the system, improvements in NWP models, and the implementation of an ensemble prediction system in an operational setting remain a potential area of further research.

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